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21000 Brookpark Road
Cleveland, OH 44135-3127
ATTN: Doug Hoder (216) 433-8705

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DESIGN AND PERFORMANCE OF THE ACTS GIGABIT SATELLITE NETWORK HIGH DATA-RATE GROUND STATION

Doug Hoder, NASA Lewis Research Center

<dhoder@lerc.nasa.gov>

Brian Kearney, Motorola Government and Space Technologies Group

<p21215@po15.geg.mot.com>

ABSTRACT

The ACTS High Data-Rate Ground Stations were built to support the ACTS Gigabit Satellite Network (GSN). The ACTS GSN was designed to provide fiber-compatible SONET service to remote nodes and networks through a wideband satellite system. The ACTS satellite is unique in its extremely wide bandwidth, and electronically controlled spot beam antennas. This paper discusses the requirements, design and performance of the RF section of the ACTS High Data-Rate Ground Stations and constituent hardware.

The ACTS transponder systems incorporate highly non-linear hard limiting. This introduced a major complexity into the design and subsequent modification of the ground stations. A discussion of the peculiarities of the ACTS spacecraft transponder system and their impact is included.

Introduction

The ACTS satellite incorporates several unique and advanced features which give it the capability for providing very wideband data service to a variety of geographical locations. These features include: wideband transponder capabilities, electronically-switched hopping spot beam antennas (also a mechanically steered antenna), 30 GHz uplink and 20 GHz downlink frequencies, and high speed switching of antenna-to-antenna connections through a high-speed electronic switching matrix (MSM or Microwave Switching Matrix).

The ACTS Gigabit Satellite Network (GSN) was envisioned to utilize ACTS' unique capabilities to demonstrate very high data rate interconnection of supercomputers and terrestrial fiber networks.

The original design of the ACTS system included a set of very high data-rate ground stations (High Burst-Rate or HBR Ground Stations [1]). The HBR stations were intended to provide wideband telephony trunking via satellite. This function was precluded by the introduction of optical fiber into the telephone network, and so were the HBR ground stations. Only one such ground station--the HBR Link Evaluation Terminal (or LET) [2] was built, although its role in the ACTS program changed dramatically from what was originally planned.

The existing Gigabit Satellite Network program is a result of a cooperative effort between NASA Lewis and the Computing Systems Technology Office (CSTO) of DARPA (Defense Advanced Research Projects Agency--now ARPA). The network was envisioned to provide optical fiber-like service through the ACTS satellite. Both agencies committed funds and personnel toward the development of the system. The original announcement for ACTS HDR stations was issued as a DARPA BAA (Broad Agency Announcement) in October, 1991 [3].

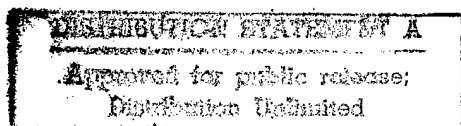
The selected proposal was submitted by BBN Systems and Technologies (Cambridge, MA), in a team with Motorola Government and Space Technologies Group (Chandler, AZ).

System Requirements and Design

The GSN system requirements were derived from interviews with potential experimenters--primarily researchers in the supercomputing field. These included: SONET compatibility, throughput up to 622 Mb/s, limited transportability, and full mesh network connectivity--utilizing the satellite-switched time-division multiple access (SS-TDMA) and hopping beam antenna features of ACTS.

The largest technical risks were associated with the 622 Mb/s data rate. Satellite transmissions at this rate were unknown, and

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NASA expected that there would be major technical problems to overcome. In order to explore the potential problems, NASA and DARPA commissioned studies into the construction of such ground stations [4] and [5]. Although the studies were probably optimistic about the cost and schedule of this program, they did provide a basis with which the government could proceed.

The design and implementation of the entire Gigabit Satellite Network is covered extensively in [6] and [7].

Configuration and Component Layout

Figure 1 is a block diagram of the High Data-Rate (HDR) Ground Station. During transportation, the entire ground station is packed into a trailer (approximately 20'L x 8'W x 10.5' H), which is typically moved by flatbed truck. The bulk of the trailer is used for storage of the antenna, base and waveguide. A small air-conditioned compartment in the front of the trailer houses the electronics. Although the ground station is packed in a trailer, it is not portable. The actual set-up of the ground station (including connection to electrical service and data networks) requires on the order of four days. The trailer functions primarily as a container and a housing for the electronics.

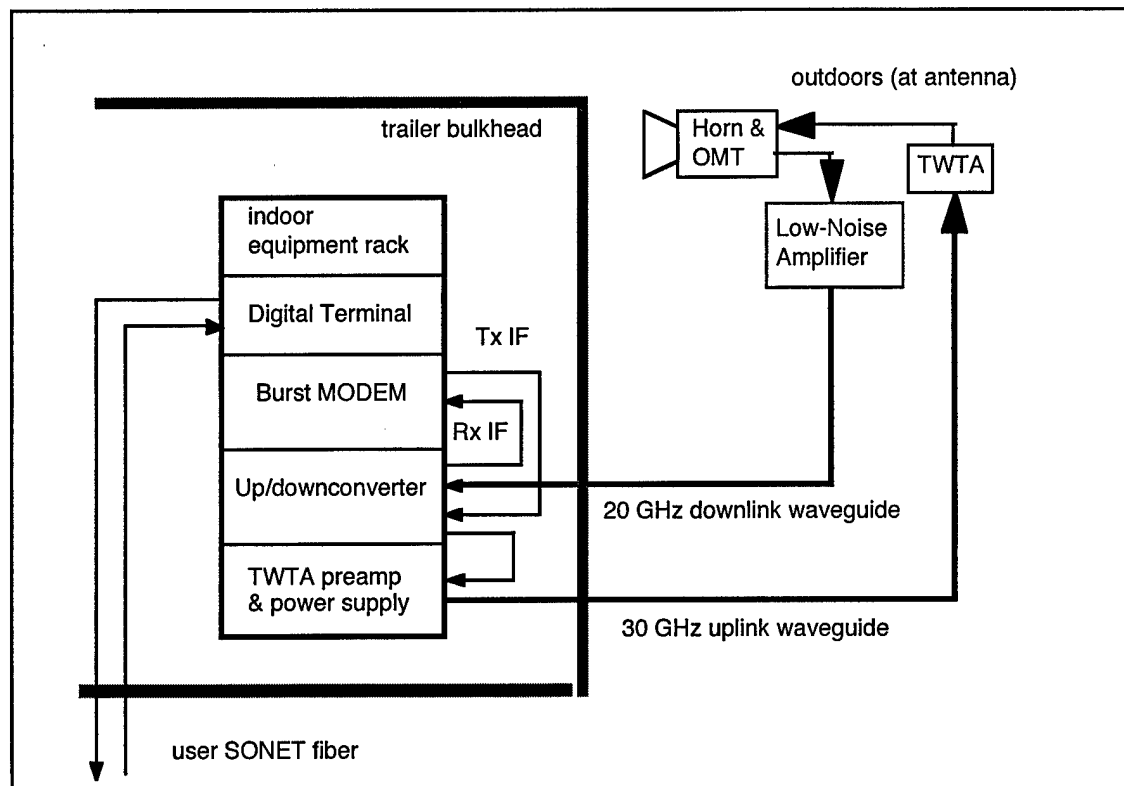


Figure 1: ACTS High Data-Rate Ground Station

The indoor (inside the trailer) electronics consist of the Digital Terminal, the Burst Modem, the Up/Downconverter and the preamp and power supply for the TWTA (the Digital Terminal is discussed extensively in [7]). The actual TWT is mounted outdoors on the antenna boom. Waveguide, power and control cables are run through the trailer bulkhead, into a raceway, out to the antenna.

The decision to put the majority of the electronics inside, and to use waveguide to and from the antenna was a compromise between providing climate-control for the electronics vs dealing with problems introduced by the long waveguide run.

A summary of the modem and ground station specifications is shown in Table 1.

Figure 2 depicts an installed ground station, and Figure 3 shows the indoor equipment rack.

<i>Table 1: HDR Ground Station Performance Parameters</i>	
parameter	design
Modulation:	BPSK or QPSK, on a per burst basis.
Modem symbol rate:	348 Msymbol/s.
Modem bit rate:	with BPSK Modulation: 348 Mbit/s with QPSK Modulation: 696 Mbit/s.
Forward Error Correction (FEC):	(232,216) Reed-Solomon forward error correcting code.
Maximum end user data throughput rate over the satellite channel:	311.04 Mb/s (BPSK) 622.08 Mb/s (QPSK)
EIRP:	> 76 dBW (with 3.4 meter antenna)
Transmit Frequency:	29.360 GHz
Transmit Spurious:	< - 30 dBc (within the ACTS passband) < - 50 dBc (outside the ACTS passband)
Transmit IF Frequency	3100 MHz
G/T:	> 28 dBK ⁻¹
Receive Frequency:	19.640 GHz
Receive IF Frequency	3100 MHz
Receive Spurious Rejection:	< - 30 dBc (within the ACTS passband) < - 10 dBc (outside the ACTS passband)
Rain-Fade Link Availability (East/West Scan, Fixed Beams) —dependent on location, BER and modulation type	> 99.0% with BER < 10 ⁻¹¹ at 696 Mbit/s (QPSK) > 99.5% with BER < 10 ⁻¹¹ at 348 Mbit/s (BPSK)
Operating temperature:	30°C to +50° C (with indoor electronics in the trailer)
Survival temperature:	-40°C to +60°C (with indoor electronics in the trailer)
Operating and storage humidity:	up to 100% non-condensing
storage temp:	-40 to +60C
Shock and vibration:	as encountered in normal shipment and hauling operation on paved roads
Corrosives:	salt atmosphere as encountered in coastal areas
Antenna wind load	operate up to 40 mph survive up to 80 mph (without tie-downs) survive up to 100 mph (with tie-downs)
Elevation angle range:	10 to 70 degrees
Antenna erection cycles:	up to 100 minimum
RF Transmit Power Monitoring	TWTA, Modem AGC signal
Loopbacks	OC-3/12 user port interface, Digital Terminal loopback, Modem digital interface loopback, Modem IF loopback RF loopback possible (with external equipment)
AC Power	3 x 30A 115Vac, 60 Hz

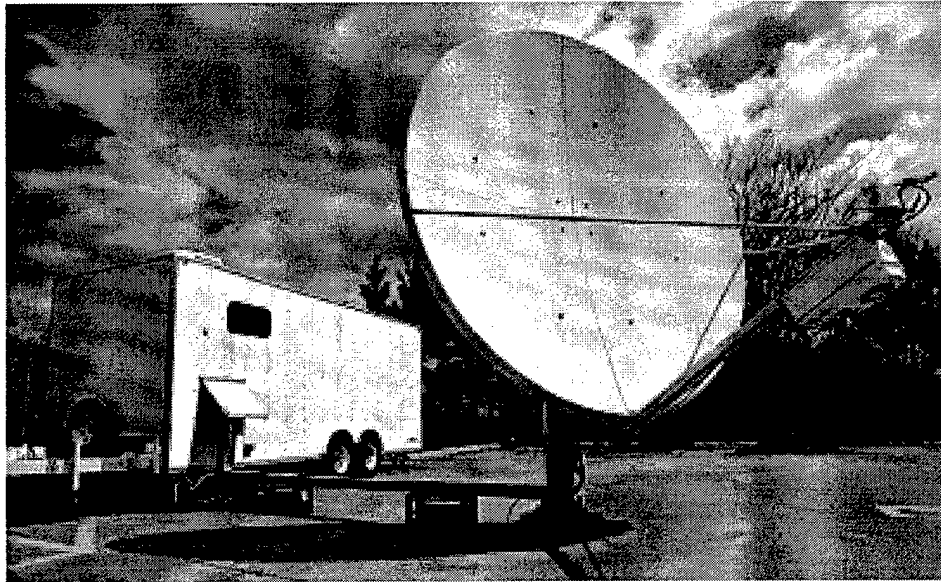


Figure 2: ACTS High Data-Rate Ground Station

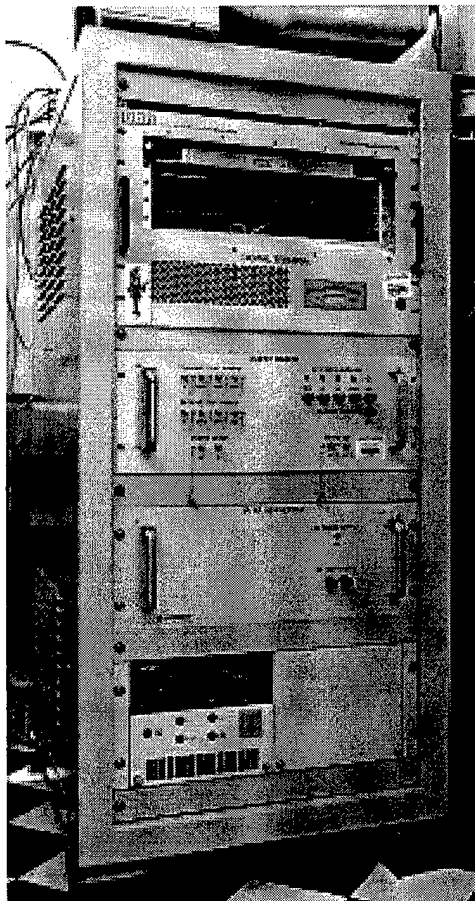


Figure 3: Ground Station Indoor Equipment Rack

Burst Modem

The Radio Frequency (RF) equipment used with the HDR Ground Stations includes some highly specialized features. The modem was developed by Motorola Government and Space Technologies Group. A block diagram of the burst modem is shown in Figure 4.

The modem is a dual-mode burst device, capable of operating with either staggered (or *offset*) binary phase-shift keying (SBPSK), or staggered quadrature phase-shift keying (SQPSK) modulation. SBPSK is essentially SQPSK but with the same signals applied to the in-phase and quadrature inputs of the modulator. This signaling format is used because it simplifies the hardware required to modulate and demodulate both formats. The SBPSK modulation is used in the network control signaling bursts (CSSC bursts) and in selected data bursts to provide better performance (at one-half the rate) on thin links--particularly those using the ACTS mechanically steerable antenna. The actual symbol-burst rate is 348 MS/s. In binary mode, this will transport 311 Mb/s, and 622 Mb/s in quadrature mode.

The key modem technologies developed for the ground station included the fast acquisition circuitry for the AGC, carrier and clock recovery functions. The initial design goal for the modem required achieving steady state performance after a 1 μ sec

preamble. To this end, the 1 μ sec preamble time was divided into 200 nsec for AGC, 400 nsec for carrier acquisition and 400 nsec for clock acquisition. After further evaluation of the system needs, the specified preamble length was increased to 6 μ sec, although the design goal of 1 μ sec was kept.

In order to meet the AGC acquisition requirement, a baseband AGC was implemented, as commercial RF attenuators do not have fast enough response time on their control ports. The baseband approach is slightly more complicated than its RF counterpart due to the requirement of having dual AGC chains for the baseband in-phase

and quadrature-phase signals. Close matching of gain and group delay is required between the two paths.

The carrier recovery circuit uses an unique approach to improve acquisition speed and remove carrier phase ambiguity. A typical carrier recovery approach is the Costas loop which is depicted in Figure 5. It utilizes a phase estimator, loop filter and VCO in its feedback loop. The problem with this approach is that it creates a four-fold ambiguity in the recovered carrier phase and has a quasi-stable lock point which tends to slow acquisition time.

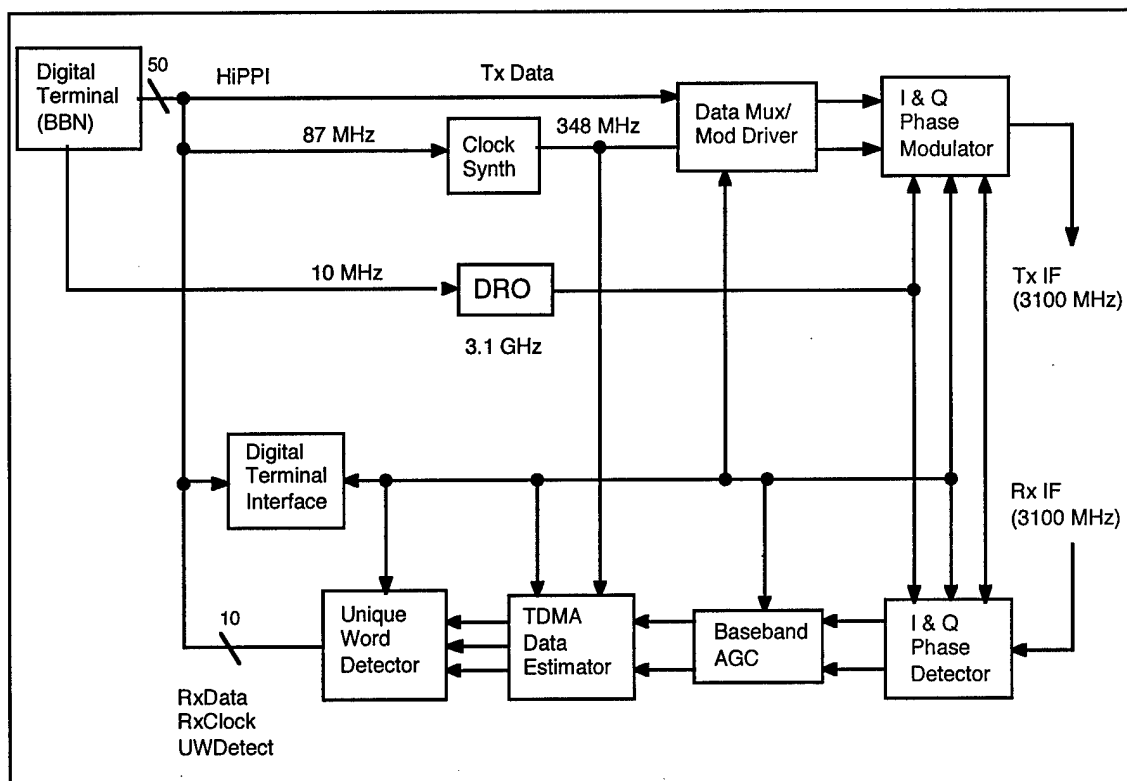


Figure 4: Burst Modem Block Diagram

The carrier recovery approach implemented in the modem uses an entirely different approach which is shown in Figure 6. The received intermediate frequency (IF) signal is converted to near baseband with a local oscillator (LO) which is close to the IF and the remaining frequency/phase offset is corrected at baseband. The phase correction is done by multiplying a complex-valued phase correction vector with the baseband in-phase and quadrature-phase signals. The complex-valued phase correction vector is generated

by complex-valued phase error estimator. The advantage of this approach is that it does not have a quasi-stable lock point, which greatly improves acquisition speed. This technique does have a disadvantage, in that it is only a first-order loop, and therefore offsets in received frequency cause carrier phase offsets. As it turns out, this causes no real problems in this application, as the only source of frequency offset is the Doppler from the satellite motion, which is too small to be of any consequence.

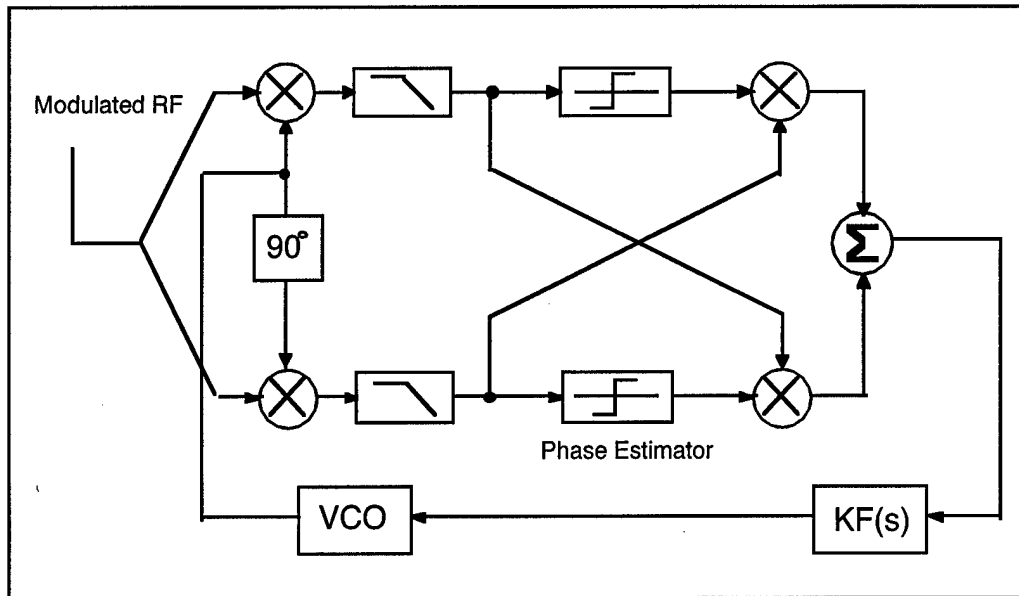


Figure 5: Costas Loop Carrier Recovery

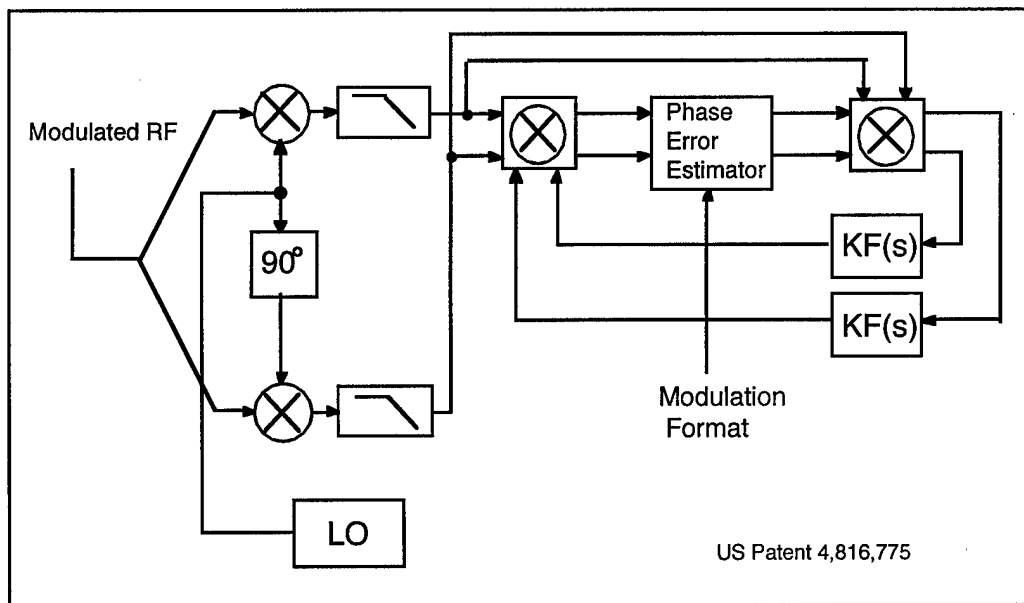


Figure 6: HDR Burst Modem Carrier Recovery

The other unique feature of the carrier recovery circuitry is the modulation format dependent carrier phase error estimator. The estimator is designed so that the lock points for the pure carrier, SBPSK and SQPSK phases of the preamble are $\{45^\circ\}$, $\{45 - 135^\circ\}$, $\{45^\circ, 135^\circ, -135^\circ, -45^\circ\}$, respectively. During the first portion of the preamble, pure carrier with 45° phase is transmitted. The carrier recovery circuitry therefore rotates the received signal until its phase is equal to 45° . At that point forward, no carrier phase ambiguity exists which is taken advantage of during the SBPSK and SQPSK portions of the burst. After the pure carrier portion, SBPSK is retransmitted and it consists mostly of phase reversals which are used in clock acquisition, and the unique word which is used for frame alignment. Since the unique word is detected as SBPSK,

there is a 3 dB improvement in missed burst performance, as compared to what could be obtained using SQPSK. Also there is a decrease in hardware for the unique word detector since only one polarity of the unique word need be detected. It should also be noted that since the lock points for pure carrier and SBPSK are a subset of SQPSK, changing from one modulation format to the next is phase continuous.

The clock recovery circuit is shown in Figure 7. Like the carrier recovery loop, it uses a complex multiplier as the actuator in the feedback loop instead of the usual VCO. As in the carrier recovery circuit, the clock loop doesn't have a quasi-stable lock point, so acquisition time is greatly reduced.

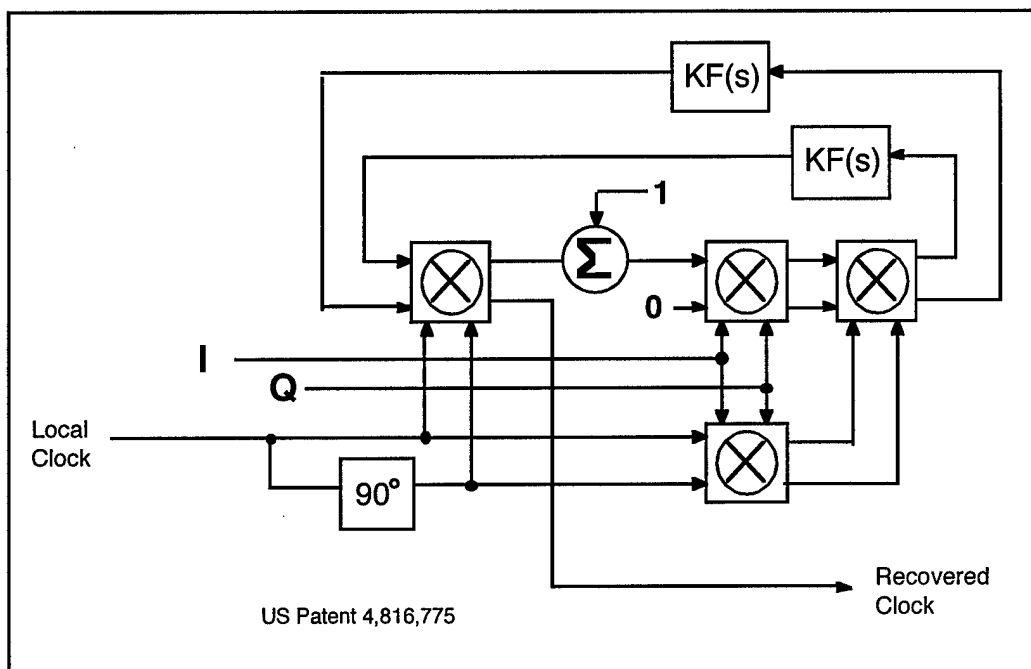


Figure 7: HDR Burst Modem Clock Recovery

The burst modem uses a mixture of both commercial and custom devices. The IF electronics are constructed from commercial connectorized parts for converting the IF into baseband in-phase and quadrature-phase signals. Processing of the baseband signals prior to signal decision uses mostly custom SSI developed by Motorola. These devices,

which include Gilbert-cell multipliers and differential amplifiers use the MOSAIC III process and have bandwidths in excess of 1 GHz. The high-speed digital circuitry primarily is implemented with Motorola ECLinPS devices. The interface between the modem and the digital terminal uses the HiPPI

standard. Further discussion of the modem design can be found in [8] and [9].

Prior to integration of the modem into the ground station, extensive laboratory testing was performed using channel and digital terminal simulators.

The digital terminal simulator was capable of varying the preamble sequence and length, the data field length and guard times. It was determined that short burst lengths were the most stressful for the modem. Consequently, most testing was done with a 32 μ sec burst, a 3 μ sec preamble, and guard times ranging from 2 μ sec to 6 msec.

The wideband channel of ACTS is extremely non-linear with AM/AM of 0.0002 dB/dB and AM/PM of 2° /dB. A channel simulator was developed that approximated the non-linearities and also provided the capability of simulating uplink and downlink noise at various levels; and burst-to-burst variations of IF power, carrier frequency and clock phase.

Laboratory testing of the modem indicated that the design met the design goals and the measured Bit-Error-Rate and Missed Burst performance is shown in Figures 8 and 9, respectively.

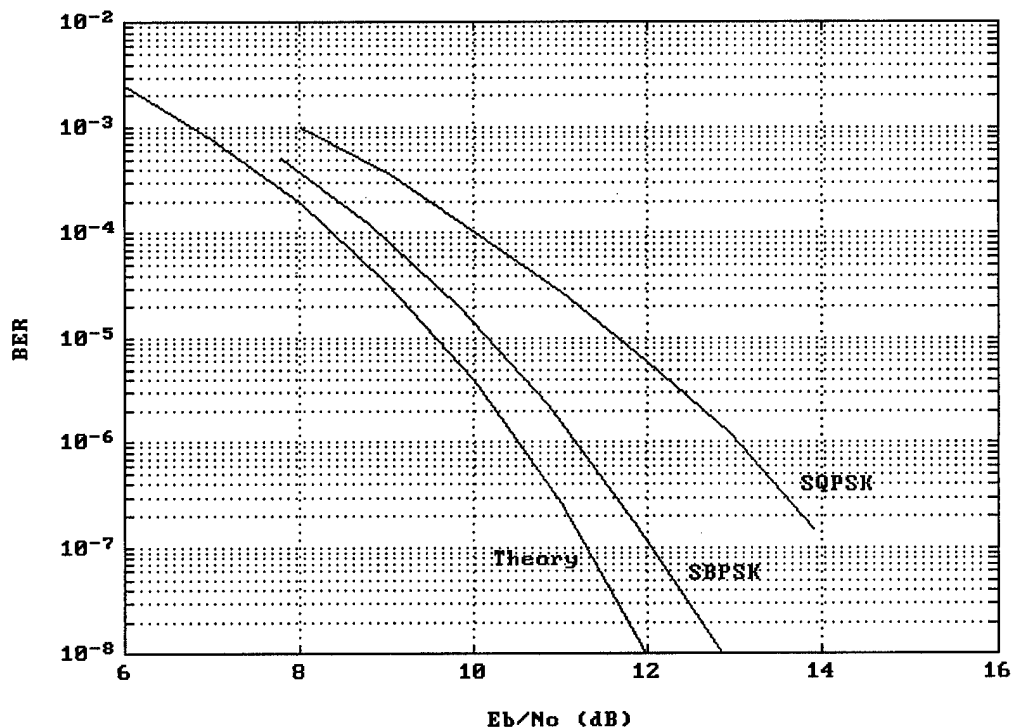


Figure 8: Burst Modem Performance with Channel Simulator

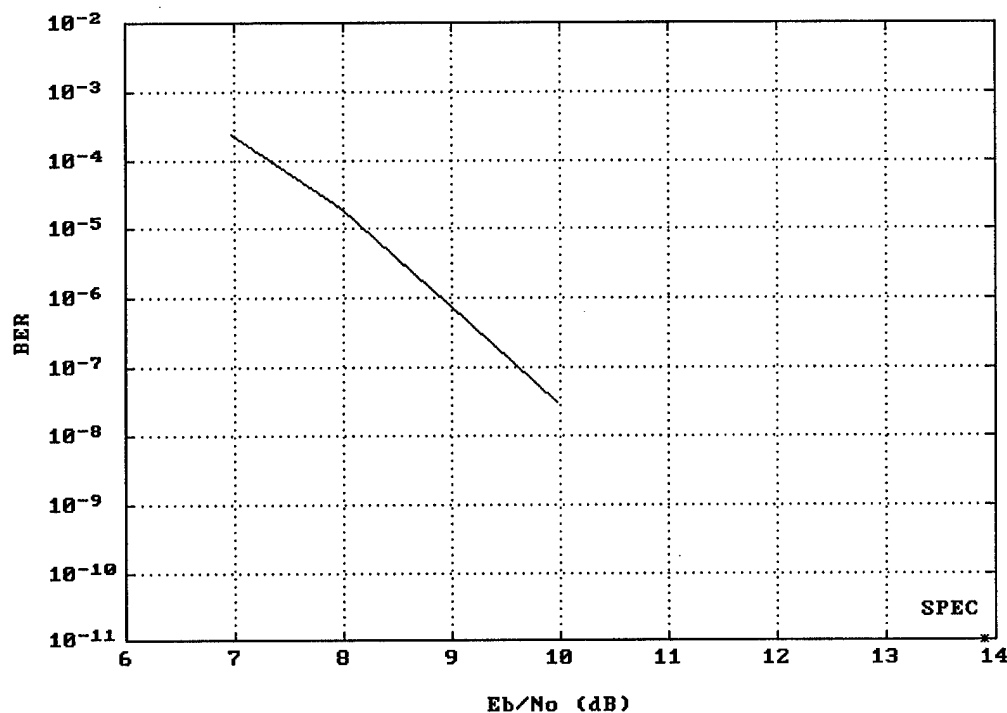


Figure 9: Burst Modem Missed Burst Performance with Channel Simulator

Up/Downconverters

The Up and Downconverters are single conversion devices, translating the 3100 MHz IF used by the modem, up to 29.36 GHz for the uplink, and down from 19.64 GHz, for the downlink. The bandwidth of both sections is greater than 800 MHz. The converter is contained in a single drawer which is mounted in the rack in the environmentally controlled compartment in the trailer enclosure. Like the modem, the converters use connectorized modular components for the RF electronics.

The Upconverter mixes the 3100 MHz transmit IF with the 26.26 GHz LO for an uplink frequency of 29.360 GHz. The Downconverter mixes the 19.64 GHz downlink RF with a 16.54 GHz LO down to a 3100 MHz receive IF. The uplink and downlink oscillators are phase-locked to a common 10 MHz system reference, derived from the spacecraft clock through the Digital Terminal's TDMA system. Although synchronization with the satellite clock is essential for the modem clock, the use of the satellite clock for the RF reference is somewhat novel. This approach provides a

common frequency reference to all the ground stations, and eliminates both drift and any offset between converter and modem pairs.

Phase noise of all the frequency sources was specified so that the combined phase noise of the communications link causes less than 0.5 dB degradation in BER performance. To meet this requirement, the SSB phase noise of both the uplink and downlink LOs was specified to be less than -118 dBm/Hz, over the range from 1 to 348 MHz.

Filtering is performed by sets of group-delay equalizers in both the uplink and downlink paths, and by filters at the antenna OMT.

TWTA

The transmitter used is a traveling-wave tube amplifier, model VZA6902V3, manufactured by Communications and Power Industries, (Santa Clara, CA) [10]. The device provides greater than 100 Watts of uplink power, and a bandwidth in excess of 1 GHz.

The RF unit, consisting of the TWT, is mounted outdoors, on the antenna boom. The indoor unit houses the high-voltage power supply and a preamp. The operating point of the amplifier is set via the front panel of the indoor unit (usually set close to saturation). A 12 m umbilical cable set is provided to run high and low-voltage power to the TWT.

Antenna Assembly

The antenna assembly consists of the antenna, TWT, feed horn, OMT (ortho-mode transducer), LNA (low-noise amplifier) and receive filter. The low-noise amplifier is manufactured by Milliwave (Diamond Springs, CA). The unit's specified gain is greater than 50 dB, and its noise figure is less than 2.4 dB. The receive filter is a 5 pole design with 750 MHz bandwidth. It provides out-of-band rejection of the transmit RF and any adjacent channels. The feed horn and OMT were provided as part of the antenna assembly.

As was mentioned above, the TWT is mounted on the antenna boom with connections to the feed horn and Upconverter made with WR-28 waveguide. Likewise, the output of the LNA is connected to the Downconverter with WR-42 waveguide. Rigid waveguide is primarily used with some flexible pieces placed at the pivot points of the antenna. For typical ground station configurations, 12 m. of waveguide is used in both transmit and receive paths. Further discussion of the waveguide and its associated problems is found in section 8 of this paper.

The antenna is a 3.4 meter offset-fed type, manufactured by Prodelin (Conover, NC). The uplink beamwidth is approximately 0.24° , with gain of 58 dBi. The downlink beamwidth is approximately 0.31° , with gain of 55 dBi. The positioner is fixed. Once the antenna is pointed, no tracking mechanism is required. Experience has shown that periodic re-pointing is not necessary.

The reflector is assembled during installation from four sections. The mast can either be set into concrete, or a large non-penetrating mount can be used. Assembly is normally done without mechanical assistance, but at

least six people are used to lift the antenna components into place.

Pointing is straightforward, as there are usually no other sources of 30 GHz energy in the sky. The reflector elevation is carefully adjusted to the value calculated for the site in question, and the antenna is then rotated in azimuth. The LNA output is connected to a spectrum analyzer, and the installers try to locate and maximize a tone transmitted from the satellite. In order to verify pointing on the antenna's main lobe, the azimuth and elevation are peaked until a C/N_0 ratio close to theory is obtained.

ACTS Compatibility Issues

The extreme hard-limiting and finite (albeit large) bandwidth of the ACTS transponder required serious consideration in the implementation of the modem and ground station.

The hard-limiting was incorporated into the transponder channel to equalize the levels of signals in the ACTS Microwave Switch Matrix (MSM). The intent of this was to reduce the effect of leakage between channels, due to the finite isolation of the switch FETs used in the MSM. The bandwidth of the spacecraft channels is reasonably flat over about 800 MHz, and rolls off rapidly beyond. As the ACTS was originally designed for a maximum throughput of 220 Mb/s (using nearly constant-envelope SMSK modulation) these characteristics did not provide any difficulty until the advent of the High Data-Rate system. These difficulties were compounded by the satellite's several stages of limiting, and the inclusion of bandpass filtering between the gain stages. Since the effect of the limiter masks the response to a swept tone, an alternative method is used to examine the spacecraft's bandwidth. A white noise response of the ground station through the satellite is shown in Figure 10.

Intersymbol interference distortion due to hard limiting can be minimized by the use of constant-envelope modulation. This was demonstrated in the use of 220 Mb/s modulation in the Link Evaluation Terminal [2]. For the HDR modem, staggered modulation was selected and filters were made as wide in bandwidth as possible, in order to provide a close-to-constant envelope.

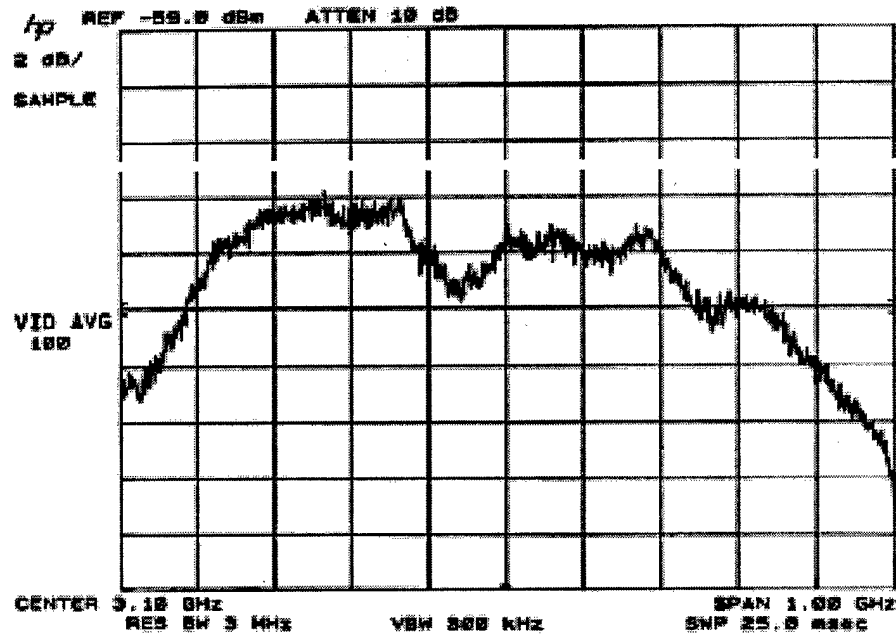


Figure 10: ACTS/HDR GS White Noise Response

The distortion introduced by the ACTS transponder system is readily apparent in the spectrographs of Figures 11 and 12. Figure 11 is a spectrograph of the ground station's

uplink, and Figure 12 shows the downlink as received through the ACTS (and the receive section of the ground station).

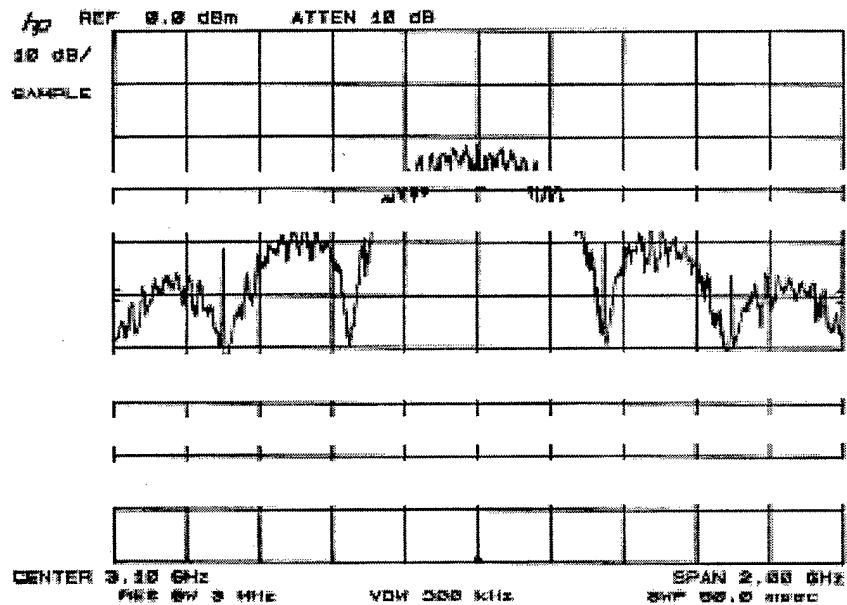


Figure 11: HDR GS Uplink Spectrum

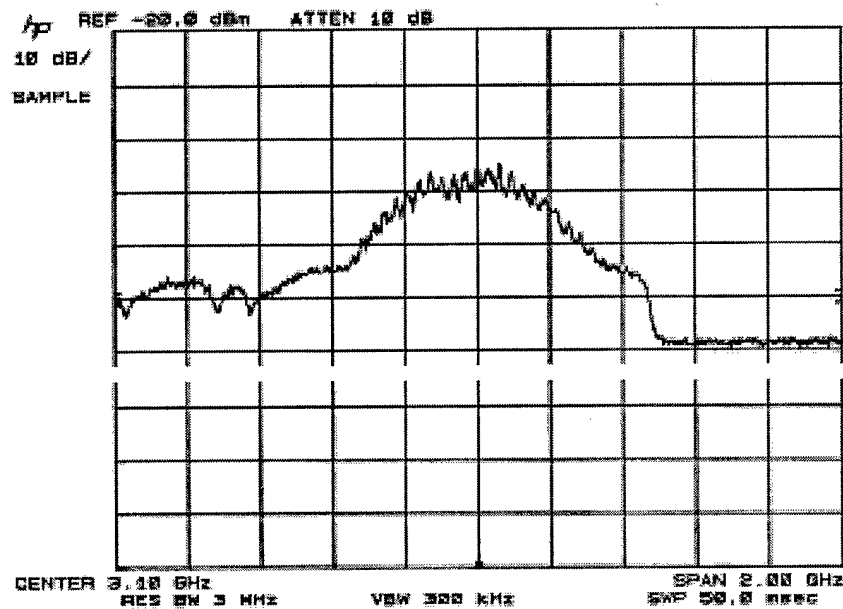


Figure 12: HDR GS Downlink Spectrum

Significant asymmetry and spectral spreading are readily apparent. (the ground station's RF frequencies were selected to put the signal in the center of the ACTS's bandwidth). Although some of this can be attributed to the ground station's receive filtering, testing with these filters removed still showed significant asymmetry.

Testing with different modulation rates revealed that the spectral distortion is a function of the ratio of signal bandwidth to transponder bandwidth--the higher the ratio, the greater the distortion. The received spectra of signals of narrower bandwidth show little of these effects [2]

A further source of intersymbol interference is the long (12 m) waveguide runs to and from the antenna, which are responsible for group delay variations of almost 3 nsec across the downlink band (19.2 to 20.0 GHz), and approximately 2 nsec across the uplink band (29.0 to 29.8 GHz). Although this variation causes only minor degradation of SBPSK performance, there is a considerable deterioration in intersymbol interference when using SQPSK.

The group delay variation is remedied with RF equalizers on both the uplink and downlink. The equalizers each consist of a cascade of three waveguide bandpass filters, designed to provide complimentary group delay to that of the waveguide.

The equalizers reduce the group delay variation to less than 1.3 nsec for the WR-42, and less than 1 nsec for the WR-28 waveguide. The effect of the equalization on the SQPSK performance is dramatic (the SQPSK mode is virtually non-functional without it) and improves the SBPSK performance by at least 4 dB as well.

Figure 13 shows the measured group delay response of 12 m of WR-42 waveguide, with and without equalization, centered at the receive frequency of 19.64 GHz.

Figure 14 shows the measured group delay response of 12 m of WR-28 waveguide, with and without equalization, centered at the transmit frequency of 29.36 GHz.

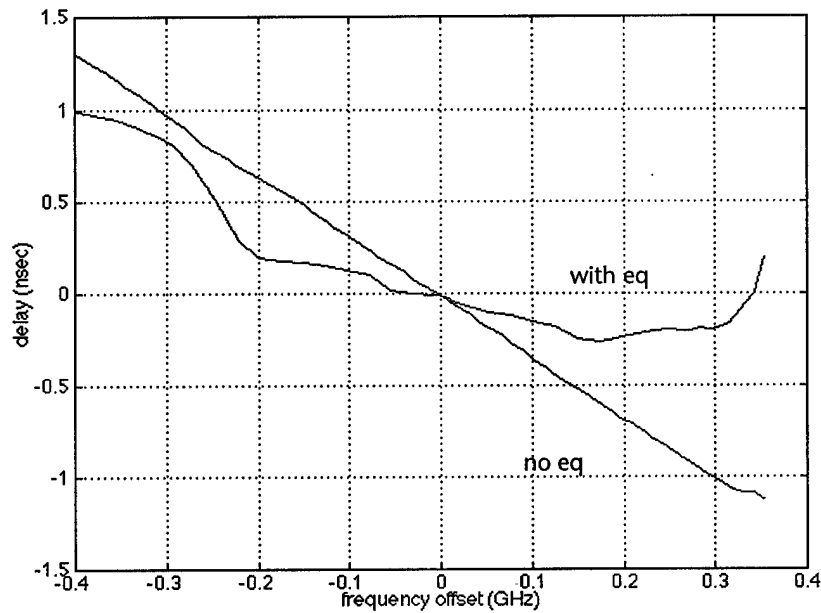


Figure 13: WR-42 Waveguide Group Delay

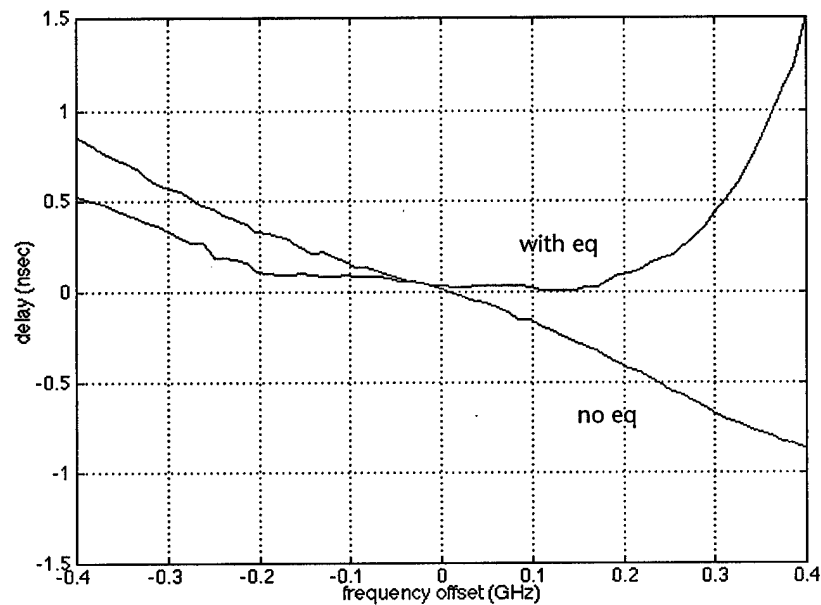


Figure 14: WR-28 Waveguide Group Delay

Ground Station Field Performance

Figure 13 shows the actual SBPSK and SQPSK performance of the ground station vs the theoretical performance of a PSK system. The

E_b/N_0 is derived from C/N_0 measurements at the ground station.

The minor degradation of the SBPSK curve is primarily due to modem implementation loss.

The further degradation in the QPSK curve is primarily due to distortions from the waveguide delay dispersion and the non-linearities of the spacecraft transponder.

Sites using the fixed and scan beam antennas typically operate at C/N_0 of better than 102 dB Hz. The SQPSK mode operates error-free down to about 100 dB Hz, and the SBPSK mode is error-free to around 94 dB Hz. This gives 2 dB margin for SQPSK, and 8 dB for SBPSK. Although small, these margins have proved to be adequate, as no major performance failures due to weather have been seen to date. For more information about link performance, see [10].

Conclusions

Overall, the program is a major technological accomplishment. All the program goals were met, with exception of QPSK BER and some rather frustrating reliability problems with several of the purchased subsystems.

Equalization of the group delay dispersion significantly improved performance, but some

additional sources of BER degradation exist which have not yet been identified.

As the ACTS was not really designed for the transmission of signals of quite this bandwidth, the overall performance can never be expected to be as good as that which could be obtained with a wider-band, more linear transponder.

The interactions between the spacecraft transponder channel and the ground station signal are not fully understood, but some general conclusions are apparent.

The hard-limiting and limited bandwidth of the transponder tend to exaggerate any shortcomings in uplink signal, such as envelope consistency, frequency response and delay dispersion, thereby increasing the intersymbol interference problem. These distortions can be ameliorated by incrementally minimizing the signal envelope variation, channel amplitude and phase variations, and if possible, the occupied bandwidth.

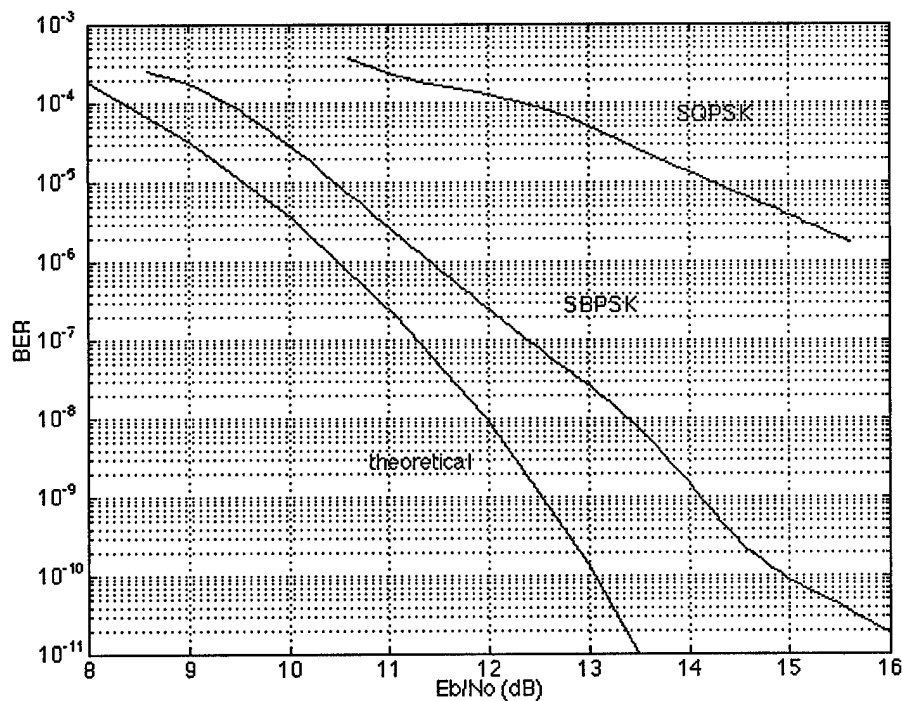


Figure 15: HDR GS BER Performance

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A special thanks to Dr Jon C. Freeman, for advice and help making the waveguide group delay measurements.